NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2052

EFFECTS OF AN AGING TREATMENT ON LIFE OF SMALL CAST VITALLIUM GAS-TURBINE BLADES

By Charles A. Hoffman and Charles Yaker

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SUMMARY

An investigation was conducted to determine the effects of an aging treatment on the life of small cast Vitallium gas-turbine blades operated at a blade temperature of approximately 1500° F and a stress of 20,000 pounds per square inch at the blade-failure plane. Twenty blades that were aged for 48 hours at 1500° F were compared with 33 unaged blades.

Aging, which has been reported to harden cast Vitallium and to improve stress-rupture life, apparently improved the time for initial blade failure, the average life, and the uniformity of life of the blades used in this investigation. The lives of the last blades to fail were not appreciably affected by the aging treatment. Statistical analysis of the blade-life data did not indicate a significant improvement in mean life or uniformity of life of the blades. This fact, however, does not necessarily prove that aging is without beneficial effects, but rather indicates that further investigation is desirable to obtain more conclusive results.

A comparison of the lives of unaged Vitallium blades with stress-rupture data for cast Vitallium bars evaluated at substantially the same conditions indicated a relation between stress-rupture life and blade life.

Both samples were progressively hardened by precipitation during operation. After about 35 hours of operation, they were at the same hardness, which increased slightly thereafter.

Metallurgical examination revealed that blade failure was initiated by intercrystalline cracking.

INTRODUCTION

A possible method of improving the times for initial failure of gas-turbine blades is heat treatment of the material in order to increase the average life, uniformity of life, or both. Investigation of the effects of aging certain high-temperature alloys has shown that in several instances improved stress-rupture properties may be obtained by such treatment (reference 1). Cast Vitallium, an alloy currently used as a turbine-blade material, has shown appreciable improvement in stress-rupture strength when aged (reference 1). Aging strengthens the alloy structure through the formation of a precipitate in the crystal matrix.

An investigation was conducted at the NACA Lewis laboratory to determine if the mean life and the initial failure time of cast Vitallium turbine blades could be increased by an aging treatment. This investigation assumed that blade failure for the particular blades investigated is, to a degree, a stress-rupture phenomenon. An indication of the effect of an aging treatment on the uniformity of life was also sought. In addition, it was desired to analyze the results obtained by objective statistical techniques in order to determine the reliability of any observed differences, and to obtain an indication of the possible reliability of the conclusions for similar investigations using the same or smaller size samples of materials with approximately the same scatter of blade life.

Twenty cast Vitallium turbine blades were aged for 48 hours at 1500° F and their operating lives were compared with those of 33 unaged blades in a small gas-turbine evaluation unit. All blades were operated on the same turbine wheel at conditions that produced a blade temperature of approximately 1500° F and a centrifugal stress of about 20,000 pounds per square inch at the expected failure zone.

Metallurgical data on structure and hardness were obtained for both nonoperated and failed blades, in order to determine differences before and after operation. The mechanism of blade failure was studied.

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APPARATUS AND PROCEDURE

Blade Operation

The Vitallium blades used in this investigation were of the following nominal chemical composition (reference 2):

C	Mn	S	Cr
0.20 - 0.35	1.00 max.	1.00 max.	25.00 - 29.00

Ni	Mo	Fe	Co
1.75 - 3.75	5.00 - 6.00	2.00 max.	remainder

Typical blades are shown in figure 1.

All blades were radiographed for internal flaws and visually examined for external flaws. The shrouds of the blades were ground to a width of 0.270 inch, a length of 0.450 inch, and a thickness of 0.070 inch in order to eliminate shroud dimensions as a variable and to produce a nominal centrifugal stress at the midpoint of the blades of 20,000 pounds per square inch at operating conditions.

Before being mounted in the turbine wheel, 20 cast Vitallium blades were aged for 48 hours at a temperature of 1500° F in a helium atmosphere, which was employed to prevent oxidation of the blades during the aging treatment. An electric-resistance furnace controlled by a commercial temperature controller accurate to ±10° F was used.

A small gas turbine, supplied with hot gases from a turbojet combustion chamber, was used to evaluate the performance of the turbine blades. The turbine operating temperatures were indicated by a thermocouple that measured gas temperature in the inlet duct 12 inches upstream of the turbine inlet. The evaluation apparatus is that described in detail in reference 3, except that in this investigation the gas inlet was at the top of the turbine instead of at the side. A thin shield of sheet metal was placed around the turbine approximately 4 inches from the inner wall of the water-jacketed housing surrounding the assembly. The space between the shield and the housing was filled with asbestos packing to catch blade fragments and thereby prevent injury of sound blades and preserve the fragments.

The turbine wheel was $9\frac{1}{2}$ inches in diameter and the blades extended $1\frac{1}{2}$ inches beyond the wheel periphery. The turbine wheel, which mounted 142 blades, is shown in figure 2. The 20 aged blades and 33 unaged blades were located at approximately equal intervals about the wheel periphery. The remaining blades in the wheel functioned only to preserve the operating characteristics of the wheel. 1231

The turbine evaluation was conducted in the following manner: Combustion air was supplied to the turbine and the turbine wheel was motored at approximately 6000 rpm for 5 minutes as a purging process for safety purposes. This period was designated motor time. Combustion was then initiated and operating conditions were achieved in approximately 3 minutes (power time). The wheel was then operated at 22,500 ±200 rpm and an inlet gas temperature of $1650^\circ \pm 15^\circ$ F until blade failure occurred (condition time). (This inlet gas temperature was estimated to yield a blade temperature of about 1500° F.) Blade failure was indicated by a change in the pitch of the sound coming from the unit. Upon failure of a blade, combustion was immediately terminated and the air flow was quickly reduced to a value such that the turbine motored at about 6000 rpm. This air flow was maintained for about 10 minutes in order to cool the assembly. Shutdowns were quickly effected in order to minimize the effects of vibration caused by wheel unbalance. The turbine wheel was then removed for replacement of blades that had failed. Fractured blades were replaced with new Vitallium blades of the shroud dimensions given. Severely cracked blades were considered failures and were also replaced in order to minimize shutdowns and the risk of injury to sound blades by flying fragments. Records were kept of operating conditions and of blade conditions at each overhaul. The turbine-wheel assembly was dynamically balanced prior to initial operation and thereafter as was necessary.

Metallurgical Examination

All blades that had failed were examined to determine fracture-surface texture and oxide coloring. In order to determine the relative grain sizes, the blades were sectioned 1/16 inch below the failure zone and mounted, polished, and electrolytically etched in 10-percent aqueous hydrochloric acid. The number of grains in the blade cross section was counted under a low-power microscope.

By use of a Rockwell hardness tester and the Rockwell A scale, the hardnesses of three nonoperated unaged blades and three nonoperated aged blades, as well as all the evaluation blades that had failed, were determined in the cross section 1/16 inch below the failure zone. The hardness readings were correct to ±1 Rockwell A unit.

Areas of blade fracture were microscopically examined to determine the mechanism of failure. In order to determine the changes in structure occurring during operation, nonoperated blades and blades that had failed of both aged and unaged samples were examined. These specimens, examined at high magnifications with a commercial microscope, were electrolytically etched in a solution of 10-percent nitric acid plus 10-percent ethylene glycol in ethyl alcohol.

Statistical Methods

Statistical parameters, which are commonly used, were employed to measure and to compare the lives of the unaged and the aged blades, and to determine the significance of changes in life. The equations and the tables used in solving the equations are set forth in standard statistical writings, such as reference 4.

The mean life and the standard deviation of the sample are, respectively:

$$x = \frac{\sum x_i}{n} \tag{1}$$

$$S = \sqrt{\frac{\sum_{1}^{n} (x - x_i)^2}{n}} \tag{2}$$

where

x mean life of sample, hour

x_i individual blade life, hour

S standard deviation of sample (measure of scatter), hour

n total number of blades in sample

The limits for a population mean, based upon particular sample evidence and assuming a normal distribution of sample means, may be stated for a given probability by the equation

$$t = \frac{(x \pm \bar{X})\sqrt{n - 1}}{S} \tag{3}$$

where

t Students t distribution for $n - 1$ degrees of freedom and for desired probability

$\bar{X}$ maximum or minimum population mean for preceding given probability

The difference in variability of the two samples, assuming they are normally distributed, may be tested by the equation

$$L = \frac{(n_1 + n_2) \log_e \hat{\sigma} - n_1 \log_e \hat{\sigma}_1{}^2 - n_2 \log_e \hat{\sigma}_2{}^2}{1 + \alpha} \tag{4}$$

where

$n_1 = (N_1 - 1)$

$n_2 = (N_2 - 1)$

N_1 and N_2 sample sizes

$\hat{\sigma} = \dfrac{N_1 S_1{}^2 + N_2 S_2{}^2}{N_1 + N_2 - 2}$

$\hat{\sigma}_1{}^2 = \dfrac{N_1 S_1{}^2}{N_1 - 1}$

$\hat{\sigma}_2{}^2 = \dfrac{N_2 S_2{}^2}{N_2 - 1}$

S_1 sample standard deviation

S_2 sample standard deviation

$$\alpha = \frac{1}{3}\left(\frac{1}{N_1 - 1} + \frac{1}{N_2 - 1} - \frac{1}{N_1 + N_2 - 2}\right)$$

The values of L have a χ^2 distribution with one degree of freedom. By use of the χ^2 distribution, the probability of obtaining a particular value of L, and hence the probability of a difference in variability, can be determined.

RESULTS AND DISCUSSION

Turbine Evaluation

The times for failure for turbine blades of the unaged and aged materials are listed in table I. The failure times for both types of blade are presented in figure 3 as cumulative-frequency (ogive) plots. The data show that aging prior to operation apparently increases the mean life, the uniformity of life, and the time for initial failure of Vitallium turbine blades. These results indicate that aging, which improves stress-rupture strength, increases blade life. The cumulative-frequency data points (fig. 3) also show that after about 73 hours of operation there is little difference in the performance of the two samples, which indicates that aging has not significantly affected the lives of the last blades to fail.

The comparative statistics for the two turbine-blade samples are listed in table II.

The statistical calculations using a posteriori probability show the probability to be 87 percent that the population mean for the unaged blades will be less than 59.5 hours; whereas the probability is 87 percent that the population mean for the aged blades is more than 59.5 hours. There is a 90-percent probability that the uniformity of life of the two samples differ, and most likely differ in the direction of greater uniformity for the aged blades. Statistical procedure recommends that 99-percent probability be considered very significant, 95-percent probability be considered significant, and 90-percent probability indicate possible significance. Significance levels substantially less than 95 percent considerably increase the risk of error in assuming a change when, in fact, there has not been one. Hence, on this basis, the results produced by aging are not highly significant and may have been due to chance, although there is some indication that aging improves uniformity. This conclusion, of course, does not necessarily imply that aging is without beneficial effect, but a statement of improvement, on the basis of these particular results, would involve a rather large risk of error. Additional investigation, with increased sample size, would be required in order to provide more conclusive indication of the effect of aging. This analysis presumes, of course, that random blade samples were used and that the blade failures were normally distributed, although departures from normality may have a negligible effect on the analysis of the mean.

It should be noted that, although the samples used were of a comparatively large size and yielded apparent differences, this fact is not necessarily an indication that there has actually been a significant change.

It is of interest to examine the specific manner in which stress-rupture properties of unaged Vitallium, cast in the shape of standard stress-rupture specimens, compare with the behavior of the unaged blades. A tabulation of cumulative failures of unaged Vitallium specimens that failed in stress-rupture evaluations at 1500° F and 20,000 pounds per square inch (plane stress in failure zone of blades) is given in table III; the stress-rupture data were obtained from reference 5. The data of table III are for specimens cast in a single heat; they therefore may be of the same chemical composition. The mean life for the stress-rupture specimen sample is 73.5 hours and the standard deviation is 25.2 hours. The cumulative-frequency curves for these data and for the unaged blades are compared in figure 4. The stress-rupture specimens had a longer mean life than the unaged blades (73.5 hr as compared to 55.2 hr). The standard deviation is slightly greater for the stress-rupture specimens (25.2 hr as compared to 20.7 hr). Calculations indicate that there is a 95-percent probability that the stress-rupture-specimen population mean is greater than 63.9 hours and that the unaged-blade population mean is less than 61.1 hours. It can therefore be concluded that there is a significant difference in population means. Also, computations indicate that there is a 95-percent probability that the actual standard deviation for the unaged-blade population will be no greater than 27.6 hours; hence, it is seen that the deviation for the stress-rupture specimen could be the same or approximately the same as that for the unaged-blade-sample standard deviation. Inasmuch as both samples may have about the same dispersion, there is a possibility that the same systematic causes of failure operate in both instances, but about different levels. An accurate comparison, however, can be made only with a larger number of items in both samples. Figure 4 can support this theory inasmuch as the two ogive curves are similar in shape and dispersion, but are displaced. Thus, there is an indication that stress-rupture data may be a primary criterion in determining blade life in a small gas turbine of the type used in this investigation.

Metallurgical Examination

Typical failures are shown in figure 5. The failure zone lies midway along the airfoil length. Figure 5(a) illustrates a blade that was removed because of severe cracking. It manifests no necking, but appears to have cracked at both edges and at the center. Figure 5(b) shows a blade that cracked at the center and one edge only. Because of the displacement of the center of area consequent to cracking, centrifugal force has bent the blade. Figure 5(c) illustrates the necking of a blade and the subsequent fracture at a point outside the region of necking. This behavior is typical of the blades that failed after necking occurred. Figure 5(d) illustrates cracking and necking outside the failure zone. These modes of failure are typical of both aged and unaged blades.

Examination of the failures of both samples indicated that cracks started in the grain boundaries and became transcrystalline as they progressed. A typical intergranular edge crack is shown in figure 6. Intergranular surface cracks also occurred at the center of the blades. This microstructural evidence indicates that under the temperature and stress conditions of this investigation, the failure progresses in its early stages along the grain boundaries. It is not known whether transcrystallinity is characteristic only of the later stages of rupture, or is present at an earlier stage. Thermal stresses apparently were not severe, because no blade warping was noted.

The textures of failure surfaces are exemplified by those shown in figure 7. The coarse crystalline surface was observed in all failures. The surface was divided into two distinct zones manifesting different oxide colors, one a dark gray and the other ranging in color from light straw to deep blue. The gray zone was present in the area where cracking first occurred; whereas the other colors were observed only on freshly fractured surfaces. There was no evidence of a fatigue type of failure in any of the fractures and, from the nature of the fractures, stress rupture is probably the major cause of failure. It is impossible from the results of this investigation to determine the extent of other factors, such as thermal shock or vibration, and whether or not they are contributing causes of failure.

The results of the grain-size measurements are listed in table IV. These data indicate a wide variation in grain size. Attempts were made to relate the blade life of both samples with grain size by determing if a simple gross correlation between these factors could be obtained. This investigation did not indicate that grain size was a strong factor influencing blade failure. Such factors as grain orientation and variations in blade dimensions, however, may have obscured effects of grain size.

The results of hardness determinations on both types of blade after turbine operation, as well as blades that had not failed, are presented in figure 8. Each point on the graph represents an average value of five readings distributed over the blade cross section. It should be noted that the unaged blades hardened rapidly and reached the same hardness as the aged blades that had not failed in about 9 hours. The presence of high stresses possibly contributed to the rapid aging. The presence of stress is known to accelerate aging in light alloys (reference 6), but it is not conclusively known whether high-temperature alloys of the Vitallium type are so affected. Both sets of used blades attained the same hardness after about 35 hours of operation, and the hardness increased slightly at approximately equal rates thereafter. These results show that failure of some unaged blades occurs before the blades reach the point where the hardness increase levels off (35 hr). No aged blades, however, failed before 35 hours, which indicates that preoperation aging resulted in the blades becoming almost fully hardened before failure. The aging period of 48 hours at 1500° F was selected to yield good stress-rupture properties (reference 1). It is apparent from the hardness data, however, that aging before operation was only partly complete. The attainment of a higher preoperation hardness might further improve performance.

Photomicrographs of unaged blades before turbine evaluation and after failure, at times ranging from 4.3 to 84.2 hours, are presented in figure 9. Figure 10 shows the structures of aged blades before evaluation and after failure at times ranging from 35.8 to 90.8 hours. The unaged material shows no precipitate before engine operation (fig. 9(a)); a precipitate is clustered about the original microconstituents after 4.3 hours of operation (fig. 9(b)); further operation shows a greater tendency for the precipitate to penetrate the matrix. By comparison, the aged sample before operation shows a precipitate close to the microconstituents (fig. 10(a)) and all aged blades that were examined after failure had a precipitate extending into the matrix. The evidence of the precipitate serves to corroborate the hardness data.

The metallurgical studies reveal differences in the hardening characteristics and the microstructure of the unaged and aged blades. This disparity suggests significant differences in the expected behavior of the two types of blade, although the direction of change cannot be indicated on this basis.

SUMMARY OF RESULTS

The investigation to determine the effect of aging (48 hr at 1500° F) on the performance of small cast Vitallium gas-turbine blades, operated at a stress of 20,000 pounds per square inch and an estimated temperature of 1500° F, yielded the following results and statistical interpretations:

1. The data obtained indicated that aging improved the life of the first blade to fail, the mean life, and the uniformity of life of the blades. The lives of the last blades to fail were not appreciably affected by the aging treatment.

2. Statistical analysis of the blade-life data did not indicate any significant improvement in mean life or uniformity of life of the blade. This fact, however, does not necessarily prove that aging is without beneficial effect, but rather indicates that further investigation is desirable to obtain more conclusive results.

3. Comparison of data for unaged blades and for stress-rupture specimens revealed some similarities, which suggests that stress-rupture characteristics and blade life are related.

4. Both samples were progressively hardened by precipitation during operation. After about 35 hours of operation, they were at the same hardness, which increased slightly at approximately equal rates thereafter.

5. Failure originated in the grain boundaries.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 26, 1949.

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TABLE I - TIME DISTRIBUTION OF FAILURES FOR

VITALLIUM GAS-TURBINE BLADES

[Temperature, 1500° F; stress, 20,000 lb/sq in.]

Unaged blades				Aged blades			
Time (hr)	Number failed	Total number failed	Total percent failed	Time (hr)	Number failed	Total number failed	Total percent failed
4.3	1	1	3	35.8	1	1	5
29.1	1	2	6	43.3	1	2	10
30.9	2	4	12	46.9	3	5	25
31.4	1	5	15	47.8	1	6	30
34.3	2	7	21	54.5	1	7	35
38.0	1	8	24	57.1	1	8	40
42.8	2	10	30	59.1	1	9	45
43.2	2	12	36	62.7	1	10	50
45.8	1	13	39	69.0	1	11	55
46.9	1	14	42	73.3	4	15	75
50.6	1	15	45	76.2	1	16	80
55.6	2	17	51	76.9	1	17	85
57.0	3	20	61	82.0	1	18	90
57.1	1	21	64	83.4	1	19	95
59.9	1	22	67	90.8	1	20	100
66.7	1	23	70				
69.0	1	24	73				
74.0	1	25	76				
76.3	1	26	79				
78.8	1	27	82				
79.3	1	28	85				
79.8	1	29	88				
83.4	1	30	91				
83.8	1	31	94				
84.2	1	32	97				
98.8	1	33	100				

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TABLE II - COMPARISON OF RESULTS OF STATISTICAL CALCULATIONS

Statistic	Equation	Material	
		Unaged	Aged
x, mean life	(1)	55.2 hr	63.6 hr
S, sample standard deviation	(2)	20.7 hr	15.2 hr
Probability of difference in population mean lives.	(3) and tables, reference 4	87-percent probability that population mean will not exceed 59.5 hr	87-percent probability that population mean will not be less than 59.5 hr
Probability of difference in variation between samples	(4) and tables, reference 4	90 percent	

TABLE III - TIME DISTRIBUTION OF FAILURES

FOR VITALLIUM STRESS-RUPTURE SPECIMENS[a]

[Temperature, 1500° F; stress, 20,000 lb/sq in.]

Total number of specimens failed	Time (hr)	Total percent failed
1	38	7.7
2	46	14.4
4	55	30.8
5	62	38.5
6	63	46.1
7	64	53.8
8	69	61.5
9	84	69.2
10	91	76.9
11	96	84.6
12	99	92.3
13	134	100.0

[a]Data obtained from reference 5.

TABLE IV - SUMMARY OF GRAIN-SIZE MEASUREMENTS OF

VITALLIUM TURBINE BLADES THAT FAILED

	Unaged blades			Aged blades	
Blade	Time for failure (hr)	Number of grains in total cross section	Blade	Time for failure (hr)	Number of grains in total cross section
1	4.3	4	1	35.8	8
2	29.1	5	2	43.3	7
3	30.9	3	3	46.9	9
4	30.9	2	4	46.9	16
5	31.4	8	5	46.9	20
6	34.3	3	6	47.8	5
7	34.3	5	7	54.5	3
8	38.0	5	8	57.1	16
9	42.8	7	9	59.1	2
10	42.8	2	10	62.7	7
11	43.2	11	11	69.0	5
12	43.2	10	12	73.3	5
13	45.8	5	13	73.3	15
14	46.9	9	14	73.3	8
15	50.6	6	15	73.3	9
16	55.6	14	16	76.2	5
17	55.6	8	17	76.9	4
18	57.0	5	18	82.0	9
19	57.0	3	19	83.4	9
20	57.0	12	20	90.8	4
21	57.1	5			
22	59.9	5			
23	66.7	6			
24	69.0	10			
25	74.0	7			
26	76.3	7			
27	78.8	9			
28	79.3	3			
29	79.8	10			
30	83.4	5			
31	83.8	2			
32	84.2	6			
33	98.8	4			

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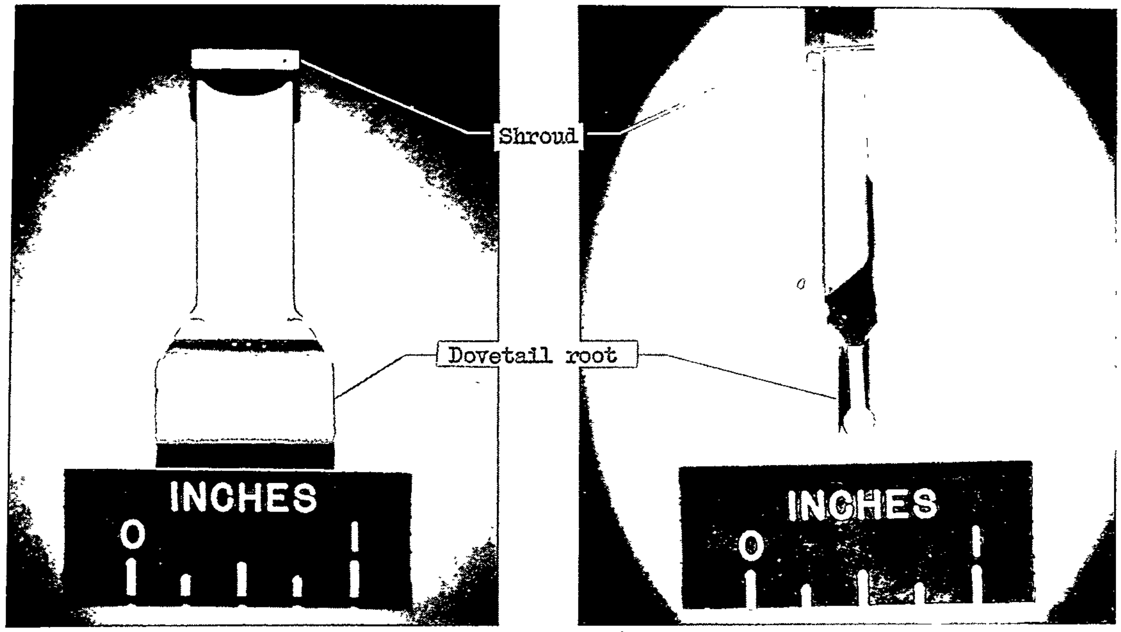
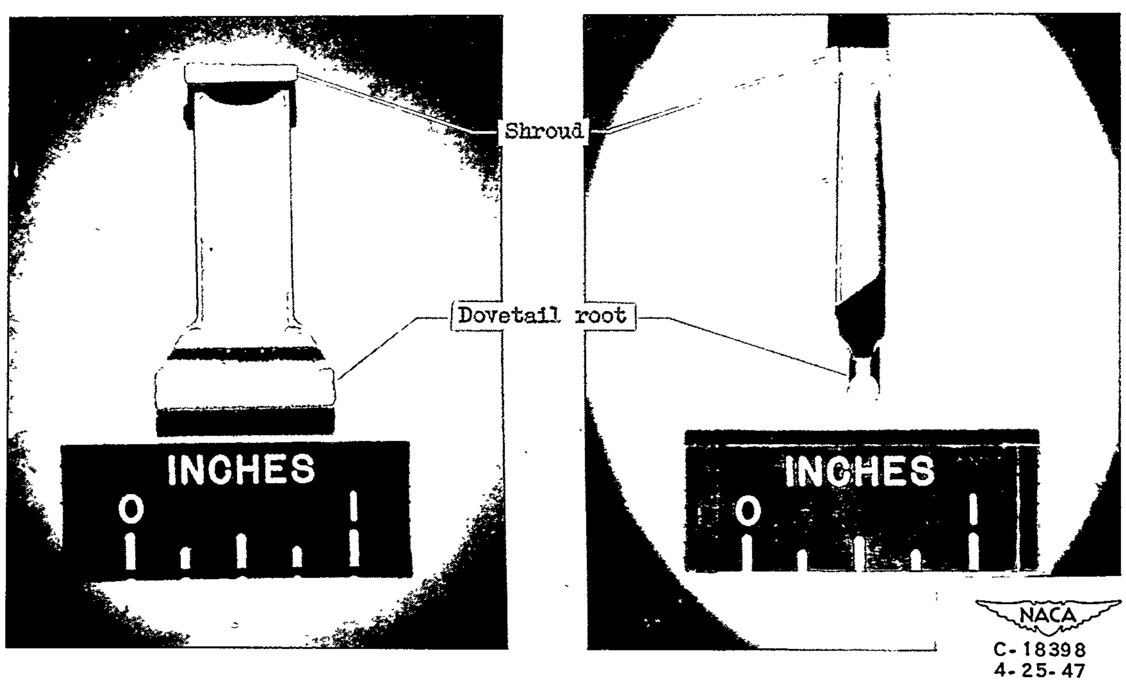


(a) Long-necked type.



(b) Short-necked type

Figure 1. - Typical gas-turbine blades.

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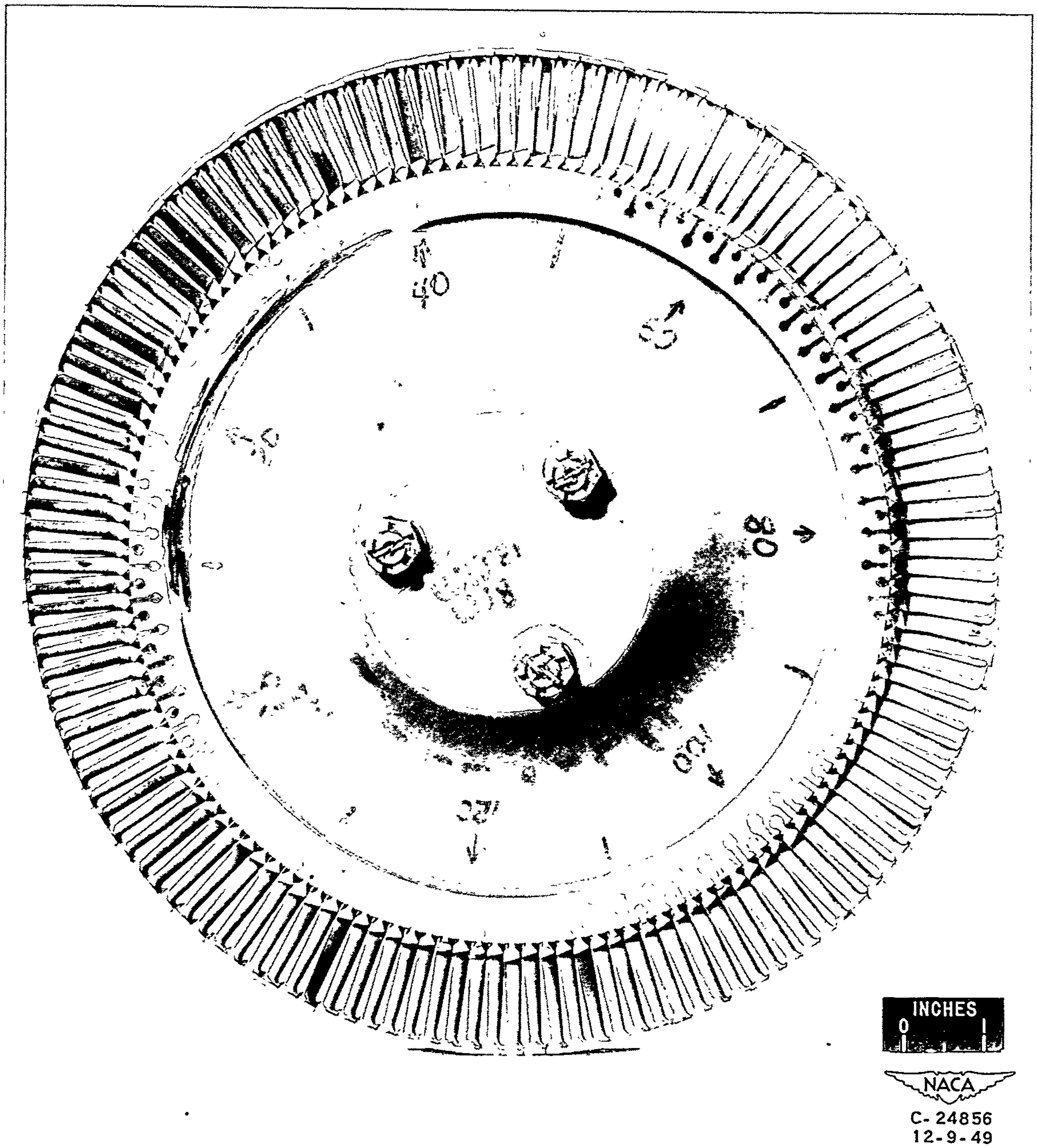

Figure 2. - Assembly of turbine wheel and blades before operation.

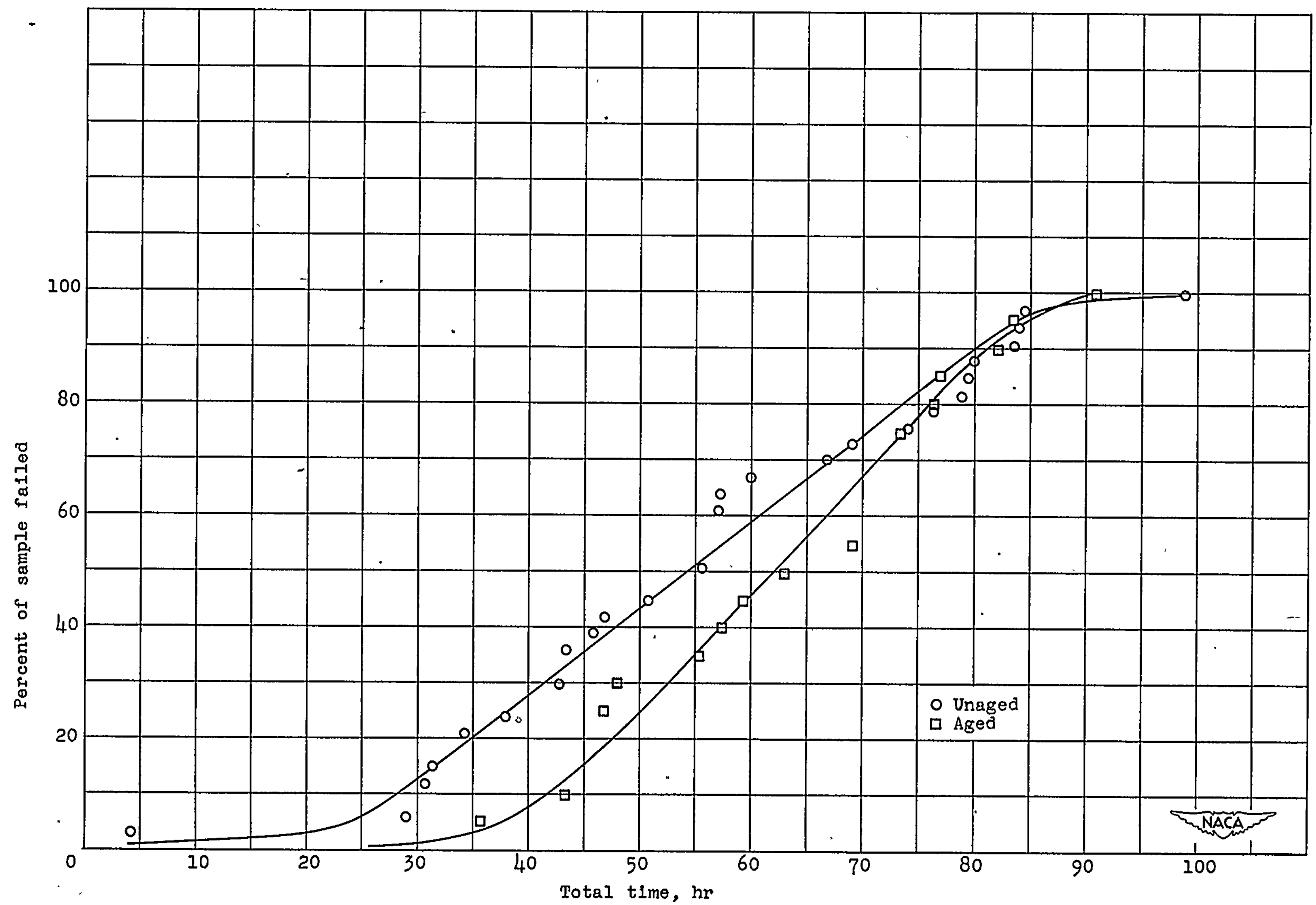

Figure 3. - Cumulative frequency of failures for 33 unaged Vitallium blades and 20 aged Vitallium blades. Temperature, 1500° F; centrifugal stress, 20,000 pounds per square inch in failure-zone cross section.

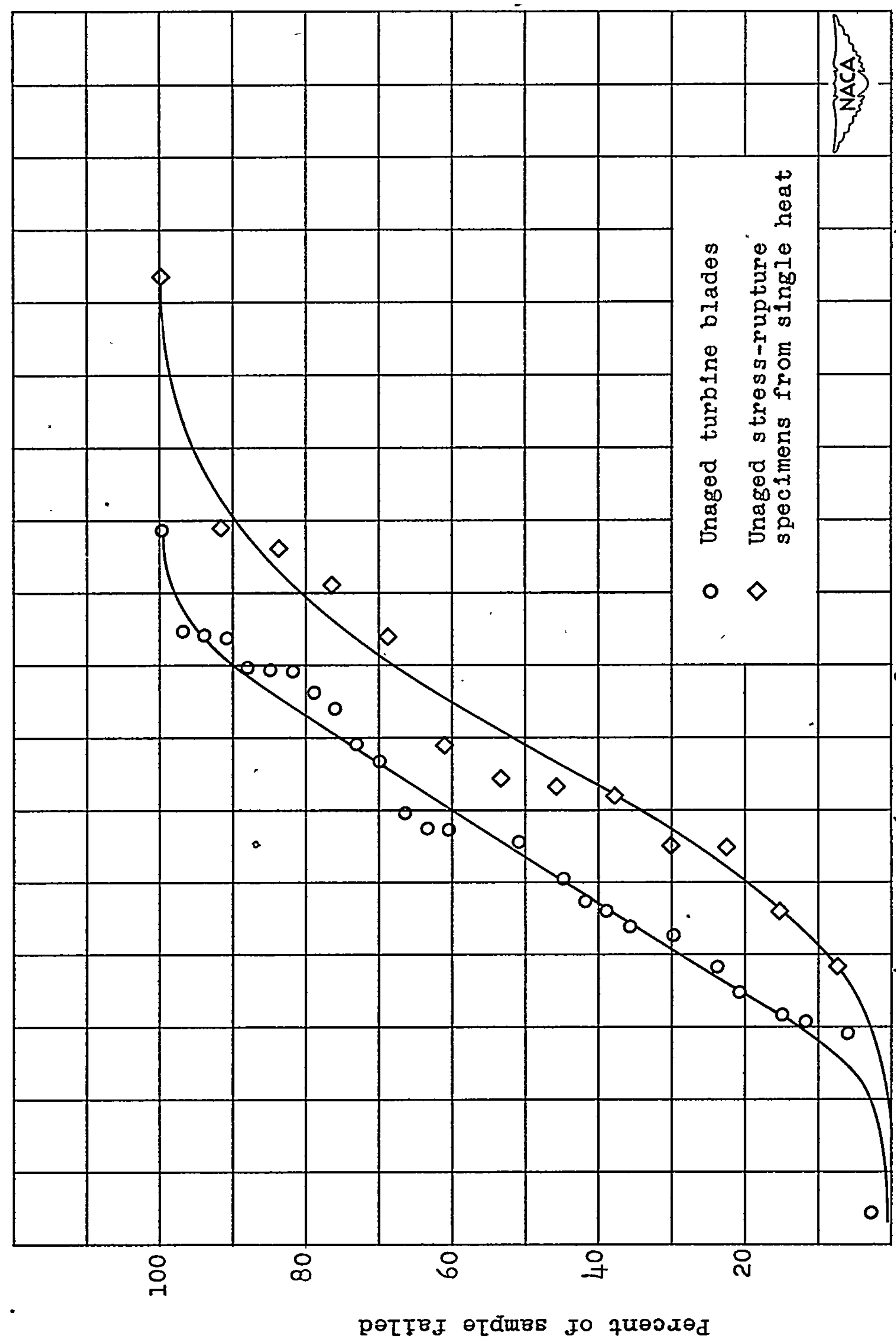

Figure 4. - Comparison of cumulative-frequency distributions of 33 unaged blades and 13 stress-rupture specimens of cast Vitallium. Temperature, 1500° F; stress, 20,000 pounds per square inch.

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(a) (b) (c) (d)

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Figure 5. - Typical blade failures. X2.

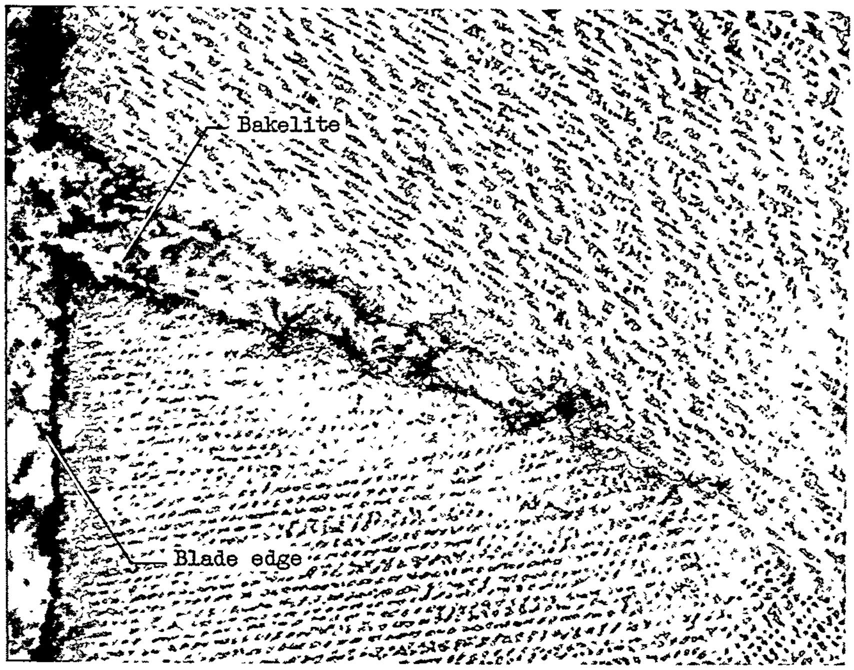

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Figure 6. - Typical intergranular crack at edge of blade. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. Vertical illumination. X50.

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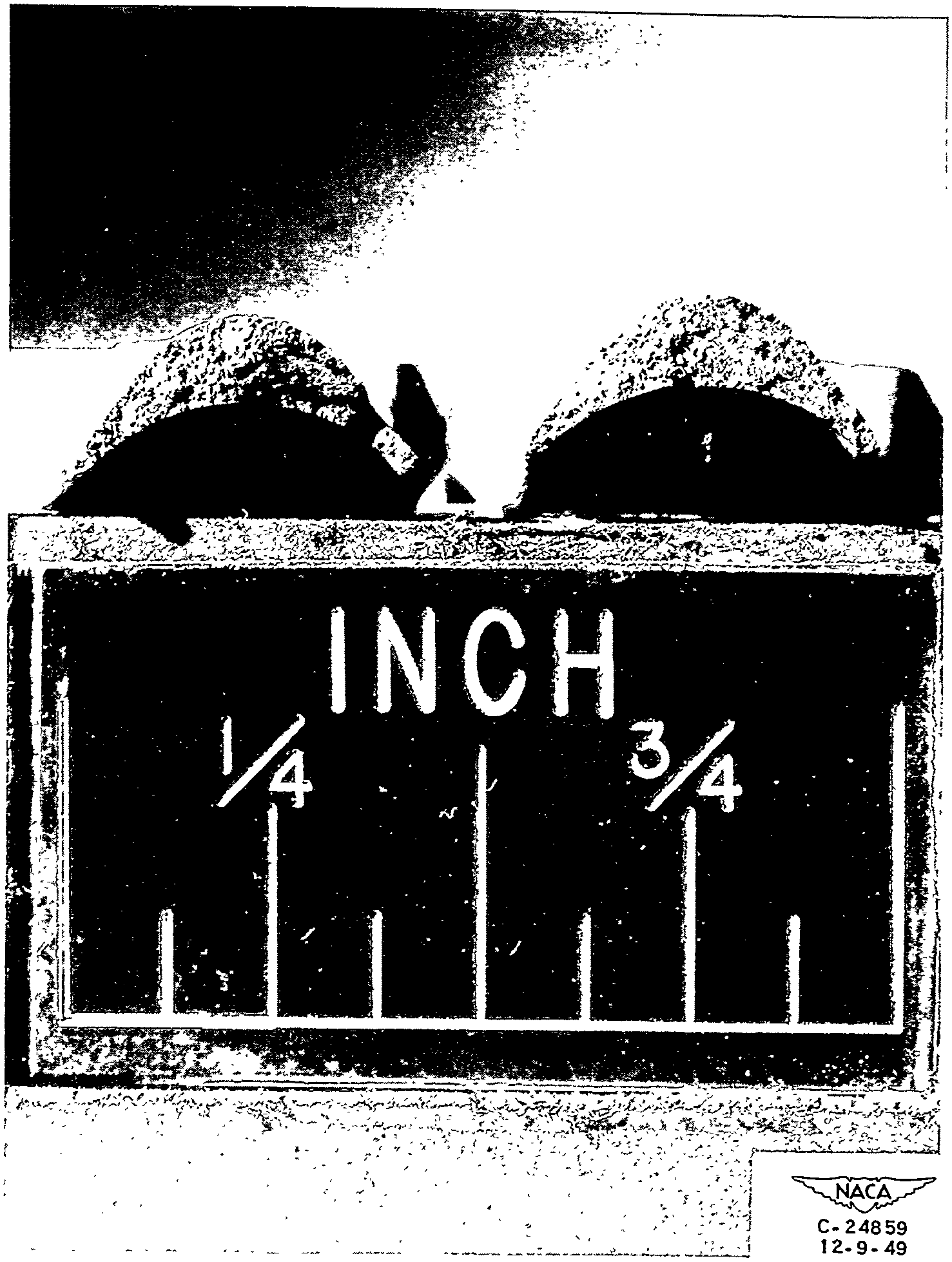

Figure 7. - Blade-fracture surfaces showing coarse crystalline texture.

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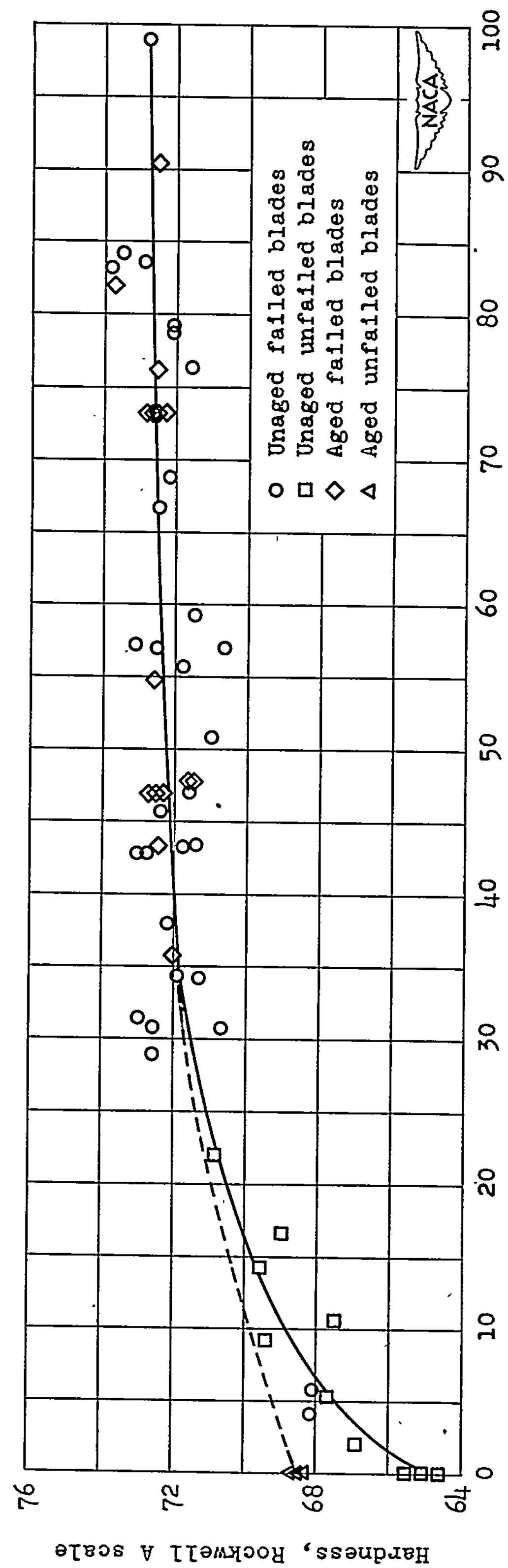

Figure 8. - Variation of hardness of turbine blades with time of operation.

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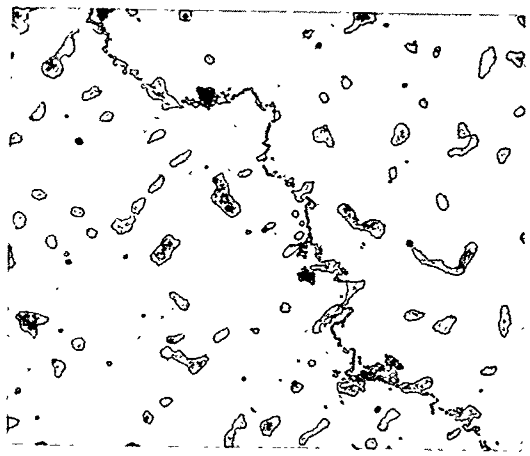
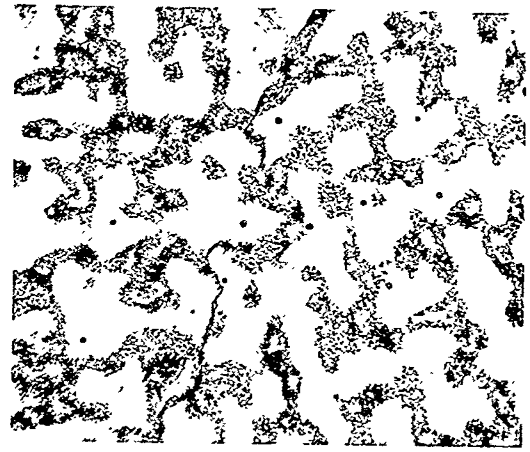
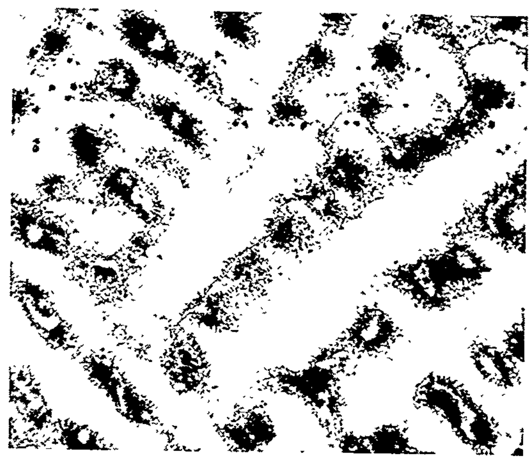


(a) Before evaluation.



(b) Failure time, 4.3 hours.



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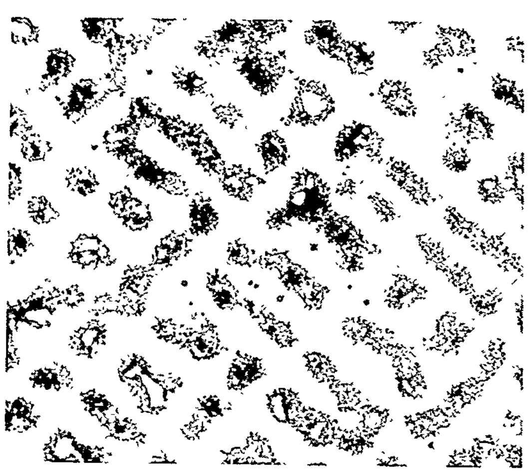
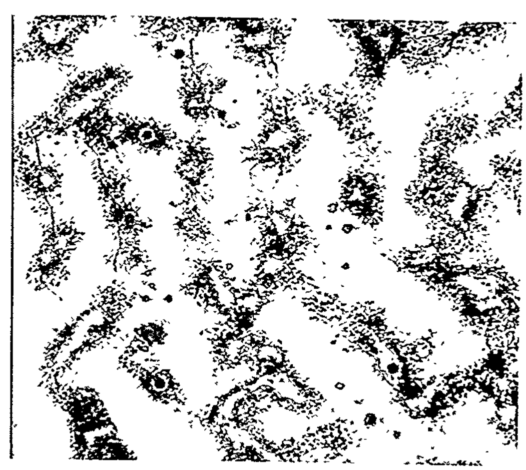
(c) Failure time, 29.1 hours.



(d) Failure time, 55.6 hours.



(e) Failure time, 84.2 hours

Figure 9. - Microstructure of unaged blades before turbine evaluation and at various failure times, showing stages of precipitation. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. X250.

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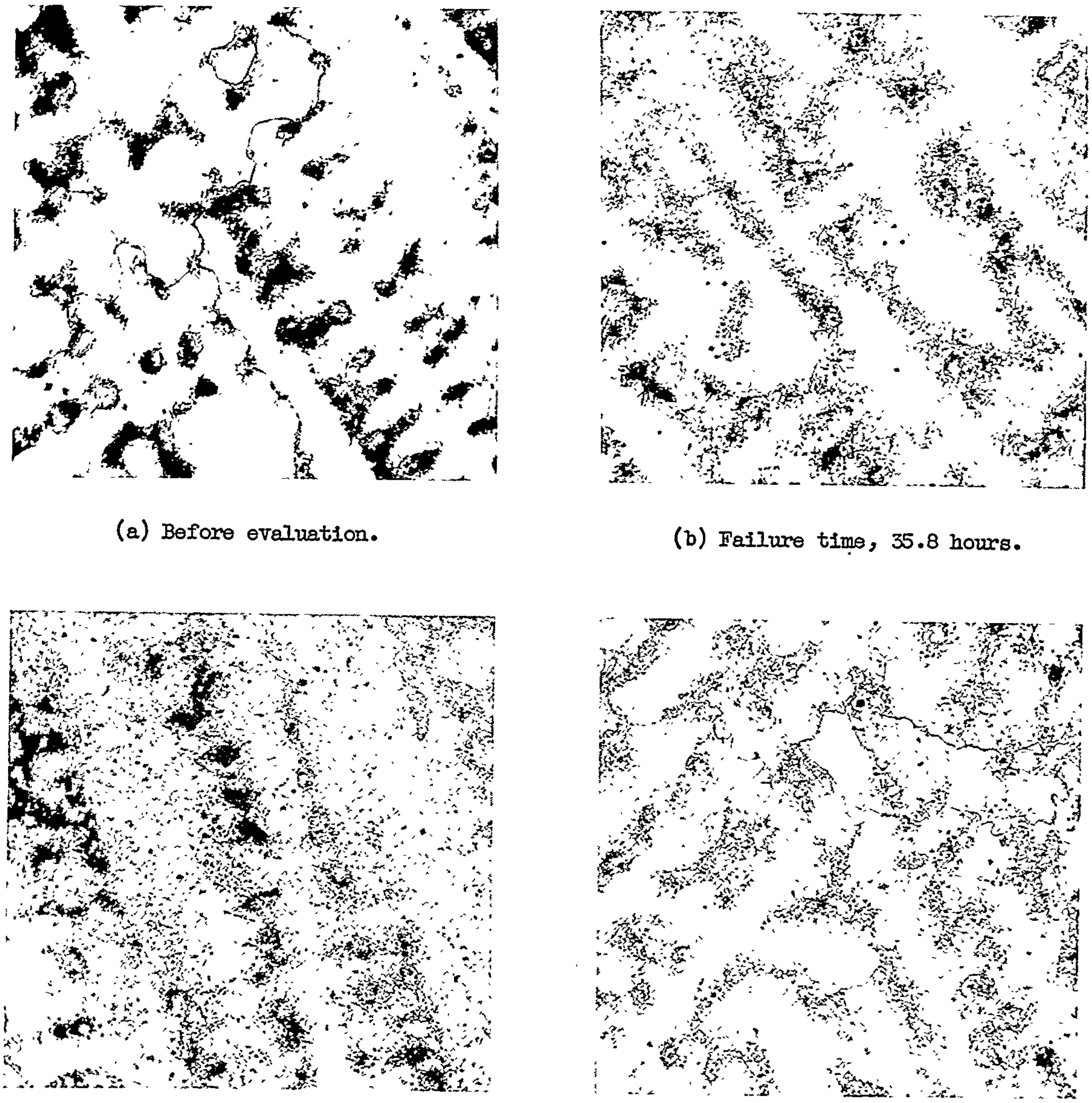

(a) Before evaluation.

(b) Failure time, 35.8 hours.

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(c) Failure time, 54.5 hours.

(d) Failure time, 90.8 hours.

Figure 10. - Microstructure of aged blades before turbine evaluation and at various failure times, showing stages of precipitation. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. X250.

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